

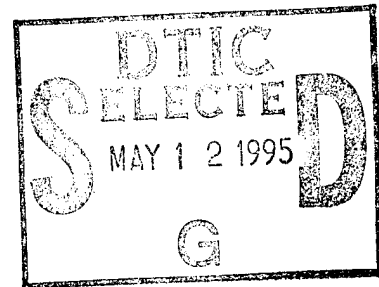
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RECENT DEVELOPMENTS IN MARITIME TECHNOLOGY RESEARCH  
INSTITUTE ACOUSTO-OPTICAL TECHNOLOGY RESEARCH

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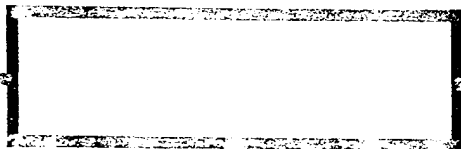
Yu Liansheng



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RECENT DEVELOPMENTS IN MARITIME TECHNOLOGY RESEARCH  
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Yu Liansheng

This article introduces recent developments in acoustic technology research at our institute in the last five years. Contents include: acousto-optical interaction theory research; acousto-optical device manufacturing technology research; acousto-optical device test measurement method research; partial acousto-optical devices, as well as applied research.

The national maritime bureau maritime technology research institute, beginning in 1974, did research work in the area of acousto-optical technology. Some progress was achieved. In conjunction with this, for over twenty domestic institutes, universities, technical schools, and scientific research units, numerous types of practical acousto-optical devices were provided. This article introduces the status of these studies in the last five years. Contents include: acousto-optical interaction theory research; acousto-optical device manufacturing technology research; acousto-optical device test measurement method research; partial acousto-optical devices, as well as applied research.

#### I. ACOUSTO-OPTICAL INTERACTION THEORY RESEARCH

As far as acousto-optical interaction theory which already exists is concerned [1-4], it has already provided R-N diffraction and Bragg diffraction analytic solutions. With regard to "transition zone" status, there are only numerical value calculations results and no analytic solutions [2]. Recently, on the foundation of theory we already have, simultaneously, attention has been paid to acousto-optical

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\* Numbers in margins indicate foreign pagination.  
Commas in numbers indicate decimals.

interaction processes which occur in the interior sections of sound carrying media and observations made of diffracted light on the exterior portions of media. New inquiries have been made into acousto-optical diffraction theory. We made use of coupling wave theory and carried out treatments of acousto-optical interactions within media. Use was made of Raman and Nath phase integration theory to handle light propagation processes. Finally, general solutions for acousto-optical diffraction were obtained. From this general solution, it is possible to derive R-N diffraction, normal and anomalous Bragg diffraction, as well as Bragg equations, Dixon equations, and similar results we already have. In conjunction with this, it explains very well such problems as asymmetrical distributions of diffracted light during oblique incidence, diffraction state criteria, and so on.

We make the following descriptions of physical processes associated with acousto-optical diffraction.

#### 1. Acousto-Optical Interaction Processes Occurring Within Sound Carrying Media

In the case of propagation of supersonic waves in media, excitation media produce polarization. This type of polarization possesses space-time distributions associated with the same rules as supersonic waves. Two adjacent ones possess the same distance between layers with the same polarization, which is supersonic wave length  $\Lambda$ . After incident light enters acousto-optical interaction media at some angle  $\theta_i$  it interacts with polarization fields, producing light scattering. Due to limitations from momentum conservation conditions, scattered light only appears in two directions. The first, along the direction of incident light, that is, the direction  $k_i$ , forms transmitted light. The second, along direction  $k_d$  forms reflected light. The direction  $k_d$  is determined from momentum conservation conditions.

$$\vec{k}_s = \vec{k}_i \pm r\vec{K} \quad (r = 0, \pm 1, \pm 2 \dots) \quad (1)$$

In the equation, the size of  $r$  is determined by  $\theta_i$  and  $\theta_B$  in Fig.1.

$$\theta_i/\theta_B = r + \delta \quad (2)$$

$\theta_B$  is the Bragg angle. Due to the fact that, generally,  $\theta_i/\theta_B$  is not equal to a whole number, the remaining numbers are represented by  $\delta$ . Considering that photons and phonons are not continuous, we stipulate:  $\delta < 1/2$  is taken as zero;  $\delta > 1/2$  is taken as 1.

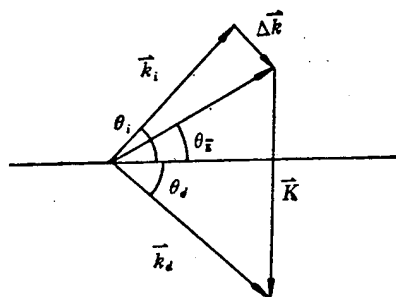


Fig.1 Acousto-Optical Interaction Momentum Diagram

## 2. Propagation Processes of Scattered Light

This process is divided into two steps. First of all, in media interiors, following along with the completion of the front scattering process and the continuation of the back scattering process, light waves propagate forward. Isophasal surfaces associated with transmitted portion and reflected portion light waves will give rise to changes.

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Due to the fact that acousto-optical interaction produced light scattering occurs inside a volume, the result is

that it is a scattering process repeated many times. In the first instance of scattering, it appears as scattered light in the direction of transmission. In the second iteration of scattering, there will be a portion which is scattered in the direction of reflection, and the reverse is also true. Reasoning by analogy from this, there is what is known as mutual coupling. The total transmission and reflection is the final result of many interactions of scattering and many iterations of coupling. As far as the mathematical description of this type of process is concerned, in fact, it is nothing else than our very well known coupling wave equation:

$$\nabla^2 \mathbf{E} - \mu \epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} + \mu \frac{\partial^2}{\partial t^2} (\Delta P) \quad (3)$$

Here, with regard to  $\Delta P$  in the equation, we made an interpretation slightly different from those in the past. [3] takes it that  $\Delta P$  is a change in the strength of acoustically caused polarization. We take it that  $\Delta P$  is a change in polarization strength given rise to jointly by supersonic waves and light waves. This type of difference is because, in past theory, the vector  $\mathbf{E}$  was used to approximately substitute for vector  $\mathbf{D}$ .

In the case of the solution of equation (3), one gets the result below [1]:

$$R = |\eta_d L|^2 \left( \frac{\sin TL}{TL} \right)^2 \quad (4)$$

Equation (4)--in theory we already have--is taken to be a description of diffraction efficiencies associated with time matched first order light. Here, we take it to be reflection coefficients within media.

With regard to isophasal surfaces associated with light waves reflected and transmitted on radiating surfaces, according to R-N theory [4], going through light travel calculations, one

obtains a phase expressing equation associated with transmitted light and reflected light. Finally, going through solutions, the phase integrals are as follows

$$E_t = \int_{-q'/2}^{q'/2} \sqrt{T'} \exp \left\{ i \left[ k_i(l - \sin \theta_i)y + \frac{\Delta \phi_i}{\cos \theta_i} \frac{\sin(KL \operatorname{tg} \theta_i/2)}{(KL \operatorname{tg} \theta_i/2)} \sin Ky \right] \right\} dy \quad (5)$$

$$E_d = \int_{-L \operatorname{tg} \theta_i/2}^{L \operatorname{tg} \theta_i/2} \sqrt{R} \exp \left\{ i \left[ Ay + \frac{2\Delta \phi_d}{KL \sin \theta_d} \cdot \sin \left( \frac{KL \operatorname{tg} \theta_d}{2} \right) \sin KDy \right] \right\} dy \\ \times \sum_{n=-N/2}^{N/2} e^{ik_n A [n_d \sin(\theta_p - \theta_d) - n_i \sin \theta_i]} \quad (6)$$

One obtains diffracted light formed at a point P in distant space by transmitted portions and reflected portions:

$$E_t = \sqrt{T'} q' J_m(\nu_1) \times \frac{\sin [k_i(l - \sin \theta_i) - mK] q'/2}{[k_i(l - \sin \theta_i) - mK] q'/2} \quad (7)$$

$$E_d = \sqrt{R} L \operatorname{tg} \theta_i J_p(\nu_2) \times \frac{\sin(A - pDK) L \operatorname{tg} \theta_i/2}{(A - pDK) L \operatorname{tg} \theta_i/2} \\ \times \sin \left\{ \frac{\Lambda}{2} (N+1) [k_d \sin(\theta_p - \theta_d) - k_i \sin \theta_i] \right\} / \sin \left\{ \frac{\Lambda}{2} [k_d \sin(\theta_p - \theta_d) - k_i \sin \theta_i] \right\} \quad (8)$$

In this,  $N+1 = q'/\Lambda$ ,  $q' = q/\cos \theta_i$ ,  $q$  is the incident light beam width;  $T'$  and  $R$  are, respectively, transmission and reflection parameters.  $m$  and  $p$  are whole numbers. The relationships between them are

$$p = (m + r)/D, \\ l = \sin(\theta_m + \theta_i), \\ A = \frac{k_i}{\sin \theta_i} - k_i \sin \theta_i - \frac{\operatorname{ctg} \theta_i}{\cos \theta_d} k_d \quad (9)$$



$$-k_d D \sin(\theta_p - \theta_d), \quad (10)$$

$$D = \operatorname{tg} \theta_d / \operatorname{tg} \theta_i, \quad (11)$$

$$\nu_1 = \frac{\Delta \phi_i}{\cos \theta_i} \frac{\sin(KL \operatorname{tg} \theta_i / 2)}{(KL \operatorname{tg} \theta_i / 2)}, \quad (12)$$

$$\nu_2 = \frac{\Delta \phi_d}{\cos \theta_d} \frac{\sin(KL \operatorname{tg} \theta_d / 2)}{(KL \operatorname{tg} \theta_d / 2)}. \quad (13)$$

The overall diffracted light at point P is:

$$\begin{aligned} E^2 &= E_i^2 + E_d^2 + 2E_i E_d \\ &\times \cos \left[ \frac{kL}{2} (\operatorname{tg} \theta_i + \operatorname{tg} \theta_d \sin(\theta_m + \theta_i)) \right] \\ &= E_i^2 + E_d^2 + 2E_i E_d \cos \\ &\times \left[ \frac{kL}{2} (\operatorname{tg} \theta_i + \operatorname{tg} \theta_d) \sin(\theta_p - \theta_d) \right] \end{aligned} \quad (14)$$

This equation is nothing else than the full expression associated with acousto-optical diffraction which we obtained. When the relationships described below are satisfied, equation (14) takes extremely large values.

$$l - \sin \theta_i = m \frac{K}{k_i}, \quad (15)$$

$$A - pDK = A - (m + r)K = 0, \quad (16)$$

$$k_d \sin(\theta_p - \theta_d) - k_i \sin \theta_i = (m + r)K, \quad (17)$$

$$\begin{aligned} &\frac{1}{2} kL (\operatorname{tg} \theta_i + \operatorname{tg} \theta_d) \sin(\theta_m + \theta_i) \\ &= 2m\pi, \end{aligned} \quad (18)$$

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or

$$\begin{aligned} &\frac{1}{2} kL (\operatorname{tg} \theta_i + \operatorname{tg} \theta_d) \sin(\theta_p - \theta_d) \\ &= 2(m + r)\pi. \end{aligned} \quad (19)$$

From equations (7)-(19), we obtain the following results.

(1) Distant field diffraction light strengths are formed from two partial transmission and reflection light beams within media. Because of this, in general situations, diffracted light striations appear in asymmetrical distributions. The light striations appearing on a reflection side are more numerous, and the other side has fewer. This is the same as experimental results.

(2) When  $\theta_i = 0$ , from equations (7), (8), (14), and (15), one obtains

$$E^2 - E_i^2 = T' q^2 J_m(\Delta\phi),$$

$$\sin \theta_m = m \frac{K}{k_i}.$$

This is nothing else than R-N diffraction results.

(3) When  $\theta_p = 0$ , from equations (16) and (17), making  $m + r$  respectively = 0 and 1, it is possible to obtain the Dixon equations

$$k_i \cos \theta_i - k_d \cos \theta_d = 0,$$

$$k_i \sin \theta_i + k_d \sin \theta_d = K.$$

Considering that  $\lg \theta_i \approx \lg \theta_d$ , and, when equal to  $\Lambda/L$ , one has

$$E_i = \sqrt{T'} q',$$

$$E_d = \sqrt{R} q' L \lg \theta_i / \Lambda = \sqrt{R} q' K^2 L / 2k$$

$$= Q q \sqrt{R}.$$

These are nothing else than anomalous Bragg diffraction results. When  $k_s = k_d = k$ , one then gets, in various directions, acousto-optical Bragg diffraction results of the same nature.

(4) It is possible to know from the equations above that the acousto-optical diffraction state criterion given by Klein and Cook:  $Q = K^2 L / 2k \cos \theta_i$ , represents, in physical terms, the ratio between the total incident light in an area in question, that is,  $\Lambda \cos \theta_i$ , and  $L^{\lg \theta_i}$ , that is, the portion of reflection produced

by mutual boundary meetings associated with the area in question and the energy within it for that portion inside the area where the interval in incident light within media is  $\Lambda$ . When this ratio value is greater than 1, only then is it possible to have the appearance of Bragg diffraction. Besides this, it is still necessary to satisfy momentum matching conditions. When this ratio value is smaller than  $1/2$ , within media, there is a transmission portion. This is nothing else than R-N diffraction.

## II. ACOUSTO-OPTICAL DEVICE MANUFACTURING TECHNOLOGY

As far as the key technologies associated with the manufacture of body wave devices are concerned, the principal ones are chemical bonding technology binding together piezo transducers and acousto-optical interaction media as well as technology for carrying out thinning of transducers already bonded on interaction media.

At the present time, domestically and outside China, normal options are for the use of three types of chemical bonding technology

### 1. Vacuum Cold Working Technology

This technology is one in which one takes transducer plates and acousto-optical media, in a film plating device, and simultaneously vapor plates of soft metal materials such as indium and tin. Following that, there is immediate compression bonding. Vacuum cold working technology requires--under a vacuum cover--installing a set of systems to add pressure. Because of this, it is necessary to make relatively complicated refits on film plating devices. Due to the fact that space inside vacuum covers is limited, each iteration is only capable of bonding one device. Work efficiency is low, and costs are high.

## 2. Vacuum Hot Working Technology

This type of technology is one in which one takes transducer plates and acousto-optical media pressure bonding surfaces and, first, vapor plates metal films. After extraction from inside film plating devices, specialized clamping apparatus takes transducer plates and acousto-optical media and clamps them together. Following this, they are again put inside the vacuum covers of film plating devices, and, under conditions of high vacuum, are heated close to the melting points of the metal films. Depending on the heat, there is diffusion bonding. With regard to this type of welding method, due to temperature not being easy to control, after cooling, there are always residual stresses. When thinness is greater, it is easy to cause transducer plate cracking. Besides this, this type of welding requires two iterations of vacuum operations. Because of this, work efficiency is also very low.

## 3. Supersonic Welding Technology

Supersonic welding is capable of using any metal to make welding layers. In conjunction with this, it is possible to carry it out under atmospheric conditions. Supersonic welding has two types--vertical welding methods and horizontal welding methods. Vertical welding methods refer to the direction of supersonic vibration and the welded surface running parallel. Horizontal welding refers to the direction of supersonic vibration and the welded surface being perpendicular. At the time of welding, it is necessary to simultaneously add a certain amount of static pressure. This type of technology, compared to the previous two types, possesses the advantages of equipment simplicity and operations in the atmosphere. However, it is generally recognized that technological conditions are not easy to master.

On the basis of the three types of technology described above, we researched a type of new technology to carry out pressure welding under atmospheric conditions. This type of welding technology operates simply, has high work efficiency and low costs. It has already successfully manufactured numerous types of acousto-optical devices with different dimensions. Many types of devices with operating frequencies within 100 MHz have already been produced in batches and supplied to users.

In regard to thinning technologies, as far as foreign reports are concerned, using general mechanical grinding, it is possible to successfully take transducer plates to thinness of approximately 10 microns. Greater thinness require using radio frequency atomization processing. Our laboratory, using mechanical grinding, has already taken LN transducer plates and thinned them down to within 30 microns. Quartz crystal chips have already been thinned down to approximately 10 microns.

### III. TEST MEASUREMENTS OF ACOUSTO-OPTICAL DEVICES

#### 1. Acousto-Optical Device Electrical Input Characteristic Measurements

The measurement schematic is as shown in Fig.2. As far as stationary wave devices are concerned, amplitude and frequency characteristic curves measured with B-15 frequency scanning graphic display devices are as set out in Fig.3. In Fig.3,  $\Delta f_1$  gives transducer band widths associated with stationary wave acousto-optical devices. Acousto-optical interaction media are acoustic loads associated with piezo transducers. The larger  $\Delta f_1$  is, the better is the chemical bonding quality shown by transducer plates and acousto-optical media. Transmission losses associated with bonding

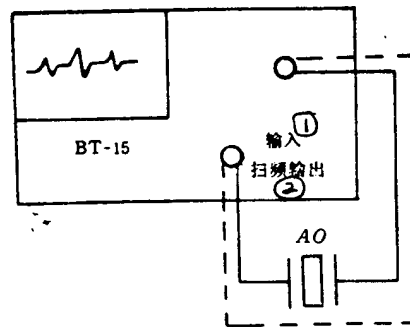


Fig.2 Electrical Input Characteristic Measurement Schematic  
Key: (1) Input (2) Frequency Scanning Output

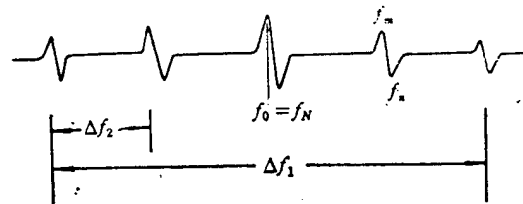


Fig.3 Stationary Wave Device Amplitude and Frequency Characteristic Curve

layers are small. Measuring  $\Delta f_1$  is one type of convenient and effective method of checking chemical bonding quality.

With regard to  $\Delta f_2 = V_2/2d$ , in it  $V_2$  is the speed of sound in acousto-optical interaction media.  $d$  is the thickness of acousto-optical interaction media in the direction of sound transmission. In the case of measuring  $\Delta f_2$ , it is possible to easily and conveniently obtain values for the speed of sound in media. At the same time, it is also an effective method of checking media thicknesses and mean motion.

$f_m$  and  $f_n$  are acousto-optical interaction media maximum and minimum admittance frequencies outside resonance frequency  $f_r$ .

$f_r = rv_2/2d$  .  $r$  is a positive whole number. The place where  $|f_m|$  and  $|f_n|$  are largest is the center transducer frequency  $f_0$ . Utilizing  $f_m$  and  $f_n$ , it is possible, from equation

$$K^2 = \frac{f_n^2 - f_m^2}{f_n^2}.$$

to solve for electromechanical coupling coefficient  $K$  associated with interaction media.

The difference in absolute values of admittance at  $f_m$  and  $f_n$  is nothing else than the diameter  $1/R$  of the admittance circle. The larger  $1/R$  is, the smaller are supersonic energy transfer losses inside media. Because of this, from differences in corresponding amplitudes at  $f_m$  and  $f_n$ , it is possible to conveniently determine the mechanical energy loss properties associated with acousto-optical interaction media.

With regard to supersonic traveling wave devices, Fig.4 is a frequency and amplitude characteristic curve example. Fig.4 clearly shows that acousto-optical interaction media act as piezoelectric transducer loads causing transducer quality factors to drop. Bandwidth widens out. The flatter curves are, the

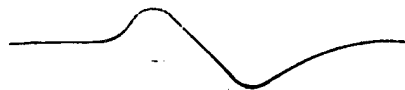


Fig.4 Amplitude and Frequency Characteristic Curve for Traveling Wave Components

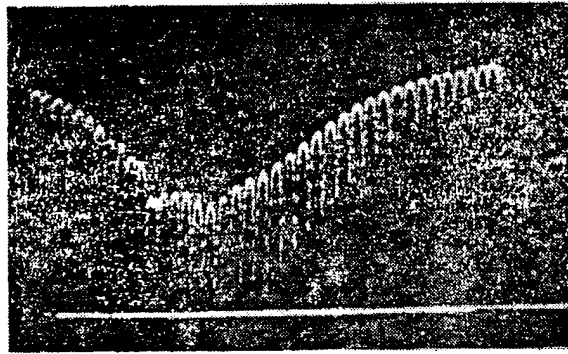


Fig.5 Amplitude and Frequency Characteristics After Tying Into Matching Network

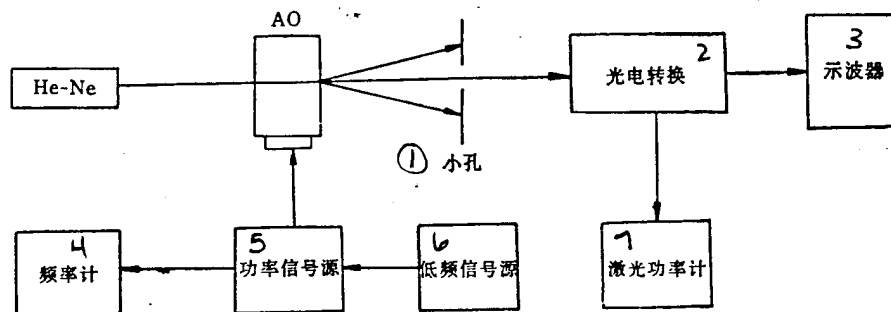


Fig.6 Optical Measurement Schematic

Key: (1) Small Aperture (2) Photoelectric Transfer  
(3) Oscilloscope (4) Frequency Meter (5) Power Signal Source  
(6) Low Frequency Signal Source (7) Laser Power Meter



TABLE 1 A COMPARATIVE TABLE OF ACOUSTO-OPTICAL DEVICE PERFORMANCE

1 生产厂家	2 型 号	3 光 波 长	4 类 型	5 衍射效率	6 驱动功率	7 中心频率
8 海洋所	AOQ-40	1.06 $\mu$ m	Q 开关 13	50%	2W	40MHz
9 国 外	AQS-244A	1.06 $\mu$ m	Q 开关 13	40%	10W	24MHz
10 海洋所	AOM-50	1.06 $\mu$ m	锁 模 14	50%	1W	50MHz
11 国 外	ML-500	1.06 $\mu$ m	锁 模 14	50%	5W	50MHz
12 海洋所	YZY3-1	0.4—0.7 $\mu$ m	调 制 15	± 6 级衍射 16	2W	10MHz

Key: (1) Producer (2) Nomenclature (3) Light Wavelength  
 (4) Type (5) Diffraction Efficiency (6) Drive Power  
 (7) Center Frequency (8) Maritime Institute (9) Foreign (10)  
 Maritime Institute (11) Foreign (12) Maritime Institute (13)  
 Switch (14) Locking Mode (15) Modulation (16) Level  
 Diffraction

larger are acoustic powers which demonstrate acousto-optical interaction media absorption. Using point electrode point by point measurements, on the basis of shifts in curve peak value points, it is possible to measure transducer plate mean motion. Fig.5 is the status tied into a matching network. The curves in question simultaneously give matching bandwidth and matching results. The height between matching locations and zero line reflects the size of mismatch.

## 2. Acousto-Optical Device Optical Measurements

Making use of the equipment shown in Fig.6, it is possible to measure the results below: diffraction efficiency; the relationship between diffraction efficiency and drive electric power; the relationship between diffraction efficiency and

incident angle; stationary wave device optical strength wave form and degree of modulation [5-7]; stationary wave device diffraction band width; the speed of sound in acousto-optical interaction media; whether or not there is a stationary wave component in traveling wave devices; modulation band width and transition time; transducer band width; matching band width.

From electrical input characteristics measurements and optical measurements, it is possible to completely understand various types of performance associated with acousto-optical devices and that electrical measurements in entire technological processes are all a type of very effective measurement means.

#### IV. PARTIAL ACOUSTO-OPTICAL DEVICES AND THEIR APPLICATIONS

Our laboratory has already supplied 100 sets of various types of acousto-optical devices one after the other to over twenty scientific research units as well as universities and specialized institutions and schools within China such as the Academia Sinica Shanghai Opticomechanical Institute, the mechanical electronics committee No.11 Research Institute, Nankai University, and so on. Recently, the Tianjin City Economics Committee Technological Reform Investment Stock Company and the Maritime Technology Research Institute combined to invest 900,000 Yuan, and, on the foundation of our laboratory, set up the "Tianjin High Technology Development Limited Stock Company", establishing our country's first specialized acousto-optical technology scientific research, production, and development unit with a planning year production value of 600,000 Yuan. In conjunction with this, it is possible to undertake various forms and types of scientific exchange activities. Technical personnel engaged in research in the area of acousto-optics provide experimental conditions.

The table above is a simple display of the performance of part of the devices which we have test manufactured as well as a comparison with foreign products of a similar type at the present time. The devices arrayed have already achieved applications in domestically test manufactured laser plate or chip etching devices as well as picosecond pulse laser systems. As far as the YZY3-1 model stationary wave device is concerned, it is a specialized teaching design and is paired with a detailed utilization manual.

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